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A Brief Survey on Cognitive Radio

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1. Introduction

With the increasing demand of wireless application, the insufficiency of spectrum is more and more serious; on the contrary, the utilization of some licensed spectrum is always low [FCC, 2003]. In order to increase the spectrum utilization, cognitive radio makes it possible for unlicensed users to access the spectrum unoccupied by licensed users.

The concept of cognitive radio is proposed first by Mitola (Mitola & Maguire, 1999), and the language for cognitive function is investigated in (Mitola, 2000). In (Haykin, 2005), the detailed expositions of signal processing and adaptive procedures are presented. In (Akyildiz et al, 2006), the major characteristics of cognitive radio networks are presented from physics layer to transport layer, as well as cross-layer design.

The spectrum agility of cognitive radio brings new challenges. The chapters in the rest of the book illustrate the wide variety of new problems for cognitive radio. The state-of-the-art strategies are presented in this chapter. To understand the general idea of cognitive radio better, the reader is encouraged to complete the brief survey before studying the chapters on specific techniques.

2. Cognitive Radio Models

Cognitive radio is a hot research topic in recent years. The wireless communication systems with cognitive radio are modelled as different models. Until now, there have been many research works on cognitive radio. Most of the works can be concluded as one of the following four kinds of cognitive radio models.

2.1 Initial Cognitive Cycle

When cognitive radio is proposed, an intelligent communication technology is expected, including observe, orient, plan, learn, decide and act (Mitola & Maguire, 1999; Haykin, 2005). The basic idea of the initial cognitive cycle is concluded as Fig. 1. The receivers obtain the channel quality information and the interference information from the surrounding radio environment by observing. After the transmitters receive the necessary feedback information from their corresponding receivers, they determine the strategies, which react to the radio environment. For more intelligent function, machine learning is adopted for estimating the utilities of possible strategies to improve system performance.

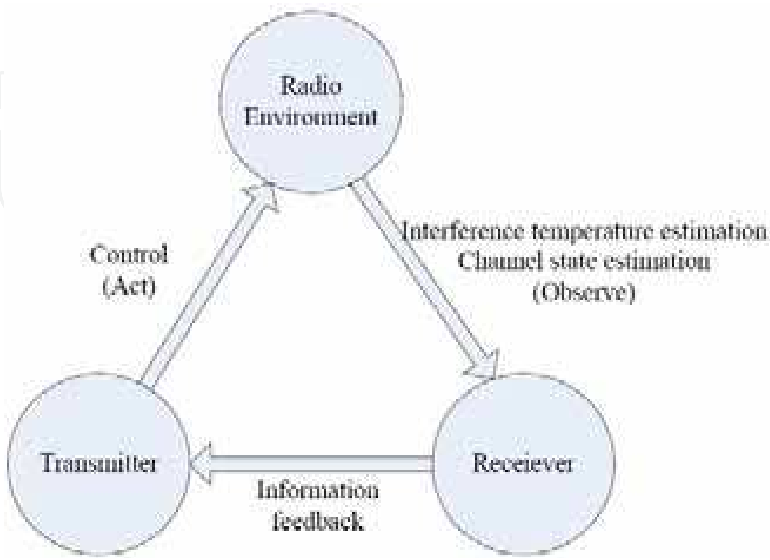

Fig. 1. Basic cognitive cycle

2.2 Dynamic spectrum model

Based on the initial cognitive cycle model, cognitive radio is studied to be utilized further for spectrum sharing between licensed/primary users and unlicensed/secondary users in licensed spectrum. In that case, the secondary users are not allowed to cause too large interference that may interrupt the communication or decrease the service quality of primary users.

In the dynamic spectrum model (Peng et al, 2006), it is assumed that the primary users may not always use the spectrum. Hence, the secondary users can opportunistically utilize the spectrum when it is not being occupied by the primary users, as shown in Fig. 2. According to the primary users' spectrum usage pattern, based on the experimental results in (Motamedi and Bahai, 2007) and (Geirhofer et al, 2007), the spectrum usage can be modelled as an ON-OFF process: ON (OFF) state represents when the spectrum is occupied (unoccupied) by primary users. The spectrum dynamics can be modelled as a semi-Markov process as in (Kim and Shin, 2008).

In this model, with perfect spectrum sensing, which means that the secondary users detect the spectrum status error-freely and justify the status in time if some primary user comes back, the secondary users and primary users do not interfere with each other. The research challenge focuses on how to discover and utilize the spectrum opportunities more efficiently. Considering the error of spectrum sensing, the possible interrupt to primary users should be investigated. The schemes need to achieve a balance of the tradeoff between the utility of secondary users and the influence to primary users.

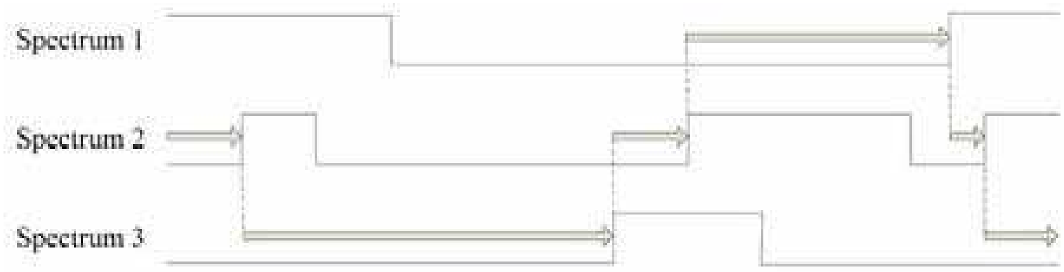

Fig. 2. Dynamic spectrum model

2.3 Interference temperature model

In the interference temperature model (Xing, 2007a), both primary and secondary users can co-exist on the same spectrum. The secondary users' interference to the primary receivers should not exceed a threshold. Interference temperature is introduced into cognitive radio by Federal Communications Commission (FCC) as a metric for the measurement of interference in a radio environment. In order to prevent the negative impact to the primary users, the interference temperature limit is used to indicate the allowed worst RF environment. In order to protect the primary users' communications, the interference caused by secondary users must be kept below the interference temperature limit at the primary receivers. That is, the primary users' Quality-of-Service (QoS) is considered acceptable if the secondary users' interference is kept below a given interference temperature limit. The maximum interference tolerance can be calculate as

$$Q_{\max} = \xi T_{\max} \tag{1}$$

where ξ is Boltzmann's constant, $T_{\max}$ is the interference temperature limit.

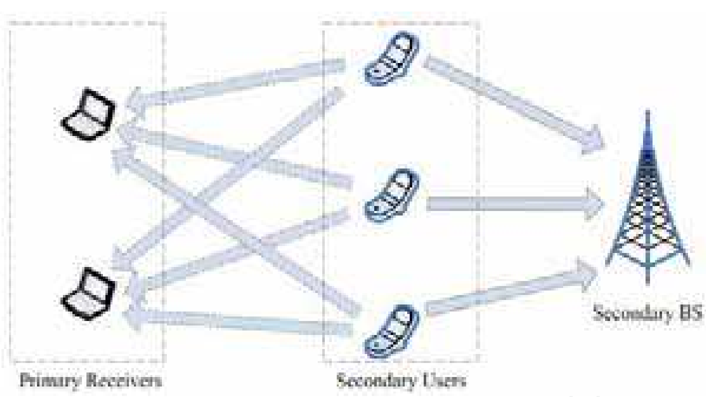

Fig. 3. Interference temperature model

(Ghasemi & Sousa, 2007) analyzes the capacity of cognitive user with the assumption that the cognitive user estimates the statistic results of its interference to the primary user through various fading channels. The average and peak interference constraints are considered respectively in (Ghasemi & Sousa, 2007). With this model, an extra interference temperature constraint is added into the problems compared with conventional wireless communication systems, as shown in Fig. 3.

2.4 Cognitive Cooperation
In (Devroye et al, 2005) and (Devroye et al, 2006), it is assumed that the cognitive user can obtain and transmit the messages that the primary user will send. The capacities of both primary users and secondary users are obtained. Based on these, (Jovicic & Viswanath, 2006) analyzes the capacity of a cognitive user who transmits simultaneously with a primary user, in the condition that the primary user can achieve the data rate just as it would in the absence of the cognitive radio user. (Cheng et al, 2007) extends the results of (Jovicic & Viswanath, 2006) to multiple access channels (MAC) and gives a heuristic scheme to achieve the maximum sum-rate.

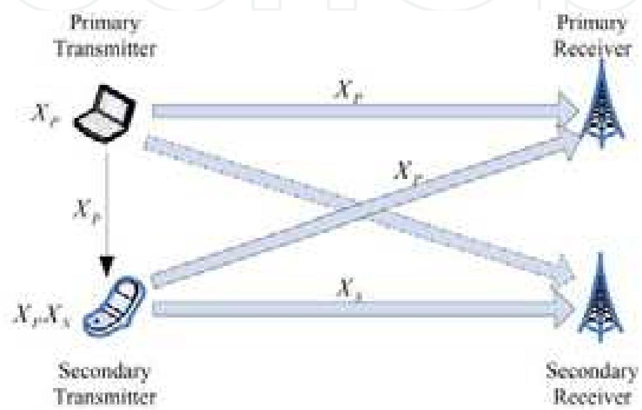

Fig. 4. Cognitive cooperation model

In this model, there exists a tradeoff that the secondary transmitter sends primary data or secondary data, as shown in Fig. 4. Transmitting primary data can increase the primary throughput and improve the capability of interference tolerance of primary users. On the other hand, transmitting secondary data can increase the secondary throughput and decrease the interference to primary users.

3. Research on Cognitive Radio Systems

3.1 PHY-layer Spectrum Sensing
Spectrum sensing is a neccesary technology of cognitive radio. With efficient spectrum sensing, the spectrum opportunities could be discovered. From PHY-layer view, the spectrum sensing can be divided into three categories, non-coherent detection, coherent detection and feature detection (Sahai et al, 2004).

The most usual non-coherent detection method is energy detection. The advantages of energy detection are short sensing time and low complexity. In addtion, it does not need any aprior information. However, because of the uncertainty of noise, there exists a SNR wall. The signal can not be detected if its SNR is lower than the SNR wall. As the signal is detected according to the signal strength, it can not distinguish different kinds of signal.

When the signal has the corresponding pilot, the coherent detection can be adopted. The matched filter is one of the coherent detection methods, but the performance is affected by high complexity, unstable time clock and the length of pilot. Because of these factors, the implement is limited in practice.

Feature detection utilizes the properties of signal to detect whether there is any primary user nearby. As the signal has periodic features because of frame structures but the noise does not have any period, cyclostationary detection can be used to distinguish the signal and the noise. Using pattern recognition, different kinds of signal can be distinguished by comparing the cyclostationary properties of the detected signal with aprior known signal properties. Although the performance is better than energy detection, the SNR wall still exists. If the signal strength is not too low, the signal can be recognized from the unstable noise.

3.2 MAC-layer Spectrum Sensing

On spectrum sensing, there exists a tradeoff between sensing time and sensing veracity. The sensing methods which have high veracity always need long sensing time. A two-level spectrum structure is proposed in (IEEE 802.22, 2006) to balance the tradeoff between these two aspects. Energy detection is adopted to discover primary users cursorily. Then, if it is possible that there exists any primary user, more elaborate spectrum sensing is deployed.

Because of the fading effect, the spectrum sensing results of one user is not always accurate. Therefore, the cooperation between secondary users is necessary (Mishra et al, 2006). There are two kinds of cooperation, centralized cooperative spectrum sensing and distributed cooperative spectrum sensing.

In centralized cooperative spectrum sensing, a centralized controller collects the sensing results from different users, and fuses the collected data altogether to obtain a table for available spectra. The results obtained by centralized cooperative spectrum sensing are accurate relatively, but it needs long sensing time, large computational capability and heave overhead.

Distributed cooperative spectrum sensing lets each user detect the signal and obtain the table of available spectrum respectively. By communicating with the neighbour users, the chosen spectrum is determined. How to sense the spectrum accurately by exchanging limited information is still an open problem.

3.3 Radio Resource Allocation

Dynamic spectrum management is an efficient method to avoid the interference between primary users and secondary users. When some spectrum is idle, the cognitive radio systems choose the spectra which have low interference. If the primary users come back to use the spectrum occupied by secondary users, the cognitive radio systems should obtain the information in time. Based on the information, the secondary users choose another spectrum from the candidate spectrum set, or decrease the transmit power to avoid too large interference to primary users if there is no other candidate spectra.
In cognitive radio networks, the power control schemes need to consider not only their own utilities, but also the influence to primary users. Game theory is an efficient method for

distributed power control (Zhu & Liu, 2007; Wang et al, 2007a). Spectrum allocation and power control affect each other, so joint spectrum allocation and power control are investigated (Wang et al, 2009a). For multi-hop networks, routing is also an important issue. The performance of cognitive radio networks can be optimized by designing appropriate routing, spectrum allocation and power control schemes.

3.4 Spectrum Marketing

On spectrum pricing, in (Buddhikot et al, 2005), a framework for coordinating dynamic spectrum is proposed. In (Xing et al, 2007b), the dynamic pricing strategy is proposed for competitive agile spectrum access markets. Sharply value in cooperative game is used to evaluate the contribution of each system in spectrum marketing (Wang et al, 2007b). The investigation on spectrum pricing is also introduced into IEEE 802.22 standardization (IEEE 802.22, 2007).

On the contrary of spectrum pricing, spectrum auction (Gandi et al, 2007; Zhou et al, 2008) is also a practical way for spectrum marketing. Each system announces a price to other systems according to the utilities and costs if it can win the auction and get the spectrum. Based the economic theory, the systems can approach the optimal performance by maximizing their own profits.

3.5 Application and Standardization

Cognitive radio is used widely in several areas of wireless communication. In (Wang et al, 2007c), the application of cognitive radio in wireless emergence networks is investigated combined with relaying to enhance the coverage performance in the disasters. In (Hinman, 2006), cognitive radio is employed for military application.
IEEE 802.22 is the first wireless standard applying cognitive radio. The secondary users use TV spectrum to improve the spectrum utilization, when it is unoccupied by nearby TV transmitters. Besides IEEE 802.22, other wireless standardization, such as IEEE 802.11n and IEEE 802.16h, also adopt cognitive radio for interference coordination among users in the same system, rather than between two systems. Many researchers are trying to use the idea of cognitive radio in LTE networks.

4. A Perspective of Future Research on Cognitive Radio

Cognitive radio is one of the research frontiers in wireless communication field. Both academic and industry researchers have large interest to cognitive radio and gained many achievements. However, there are still some research challenges as follows (Wang, 2009b).

1) Cooperative Sensing: Distributed cooperative spectrum sensing needs further research to balance the tradeoff between accurateness and overhead better.

2) Cognitive Relaying: Using additional user to relay the data can increase the throughput for either primary links or secondary links. In addition, relaying for primary links can increase the data transmission for more spectrum opportunities, and relaying for secondary links can decrease the interference to primary users.

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3) Cognitive MIMO: MIMO can decrease the interference by adjusting the signal orthogonal to the interference channel to primary users (Zhang & Liang, 2008). Therefore, using multiple antennas is helpful in cognitive radio networks to increase the throughput of secondary users and decrease the interference to primary users.

4) Femtocell: As the characteristics of femtocells, the interference decreases a lot because the signal usually penetrates walls, which is very favourable for cognitive radio to avoid interference.

5) Robust Cognitive Radio: In most of the exist research works, the radio resource allocation is investigated based on perfect spectrum sensing results. Considering the error of spectrum sensing, the resource allocation schemes should restrict the outage probability that secondary users interrupt the communication of primary users.

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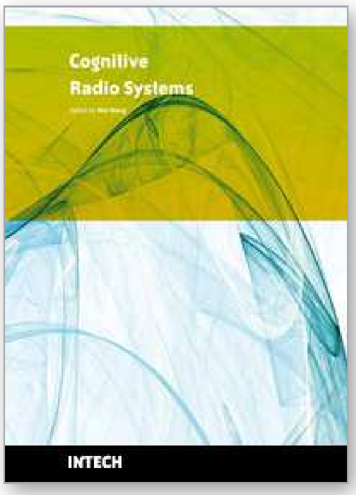

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Cognitive radio is a hot research area for future wireless communications in the recent years. In order to increase the spectrum utilization, cognitive radio makes it possible for unlicensed users to access the spectrum unoccupied by licensed users. Cognitive radio let the equipments more intelligent to communicate with each other in a spectrum-aware manner and provide a new approach for the co-existence of multiple wireless systems. The goal of this book is to provide highlights of the current research topics in the field of cognitive radio systems. The book consists of 17 chapters, addressing various problems in cognitive radio systems.

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